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Effectiveness of desalination powered by a tracking solar array to treat saline bore water

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Abstract

A solar powered desalination unit was tested between October 2008 and February 2010 in the Brisbane Botanic Gardens, Mt Coot-tha, Queensland, Australia to provide garden irrigation during drought conditions. Water was extracted from a saline bore, and the salt removed with a 30kL per day brackish borewater desalination unit. The driving force was provided by a bore pump driven by a 1.44 kW tracking solar array. This study demonstrated that solar powered desalination of saline bore water delivered fresh water to the rated flow rate of the RO membrane rack during periods of sunshine. During periods of overcast or rainy weather, the performance of desalination decreased. Consumption of permeate for flushing further reduced overall recovery rate during rainy weather. Solar desalination performance was inversely related to the El Niño Southern Oscillation Index (polynomial fitting $R^2 > 0.4$). Analysis of performance in relation to satellite-derived daily horizontal solar radiation shows stronger correlation with permeate production.

Brine by-products flowed uphill via the residual pressure in the concentrate line onto a marine plant culture on the slopes of Mt Coot-tha, supporting an associated research project on brine treatment addressed in a future publication by the present authors and others. The graphical abstract Figure 1 illustrates our installation. In conclusion we found solar desalination performance is hindered in wet weather, but otherwise our design was among the most efficient brackish water systems described in the literature.

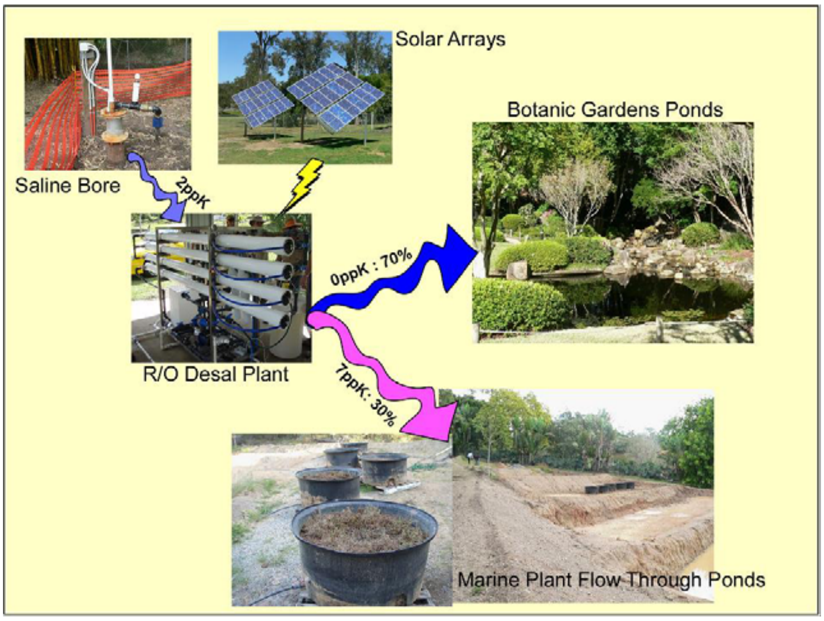

Figure 1: Green Powered Desalination at the Mt Coot-tha Botanic Gardens, 2008-2010
(Graphic produced by Jock MacKenzie [1])

1 Introduction

Solar desalination is any technique that desalinates water using solar energy. In general, there are two leading techniques: Indirect use of photo-voltaic electrically applied to mechanically drives pumping through reverse osmosis (PV-RO) and solar-thermal driven humidification-dehumidification or membrane distillation.

Reverse osmosis (RO) is a pressure-driven process that forces the separation of fresh water from other constituents through a semi-permeable membrane. This is the preferred method in large-scale desalination in processes where grid electricity is used.

Advances in pumps and declining energy costs (be they renewable or fossil fuel generated) have caused RO systems to be more viable than humidification-dehumidification systems [2, 3]. Recent developments of solar thermal distillation have recently been competing with PV-RO [4]. Reductions in the cost of PV panels has increased competitiveness with fossil fuel driven RO, with hybrid solutions often proving to be most economical [5-9].

Early reports on PV-RO prototypes were promising [10-12] and there are several reports of laboratory bench tests [13, 14]. A PV driven seawater desalination process, without batteries, was published a couple of years later [15]. Reviews of PV-RO case studies have been published, but they are not clear on operational performance at times of poor sunlight [16, 17]. Hypothetical stand-alone PV-RO performance has been modeled for various levels of sunshine hours and salinities of the feed water [18].

Horizontally fixed PV systems obtain only the product of efficiency and the global horizontal irradiation (η·GHI). Tracking PV arrays obtain the product of the efficiency and the direct normal irradiation (η·DNI), plus the viewed fraction of the global horizontal irradiation and ground reflectance. In this respect our system was more effective than others with fixed PV panels.

Some other PV-RO systems may have exposed brackish feed water to atmospheric pressure in the process of pretreatment, requiring re-pumping to overcome the osmotic pressure to obtain permeate. In this respect, our system conserved the pressure energy of feed water emanating from the bore pumps. It also must be said that there was about one meter of artesian pressure on the well head, and so the combination of these factors resulted in lower solar pumping duty than may have been the case for others.

The PV-RO pilot is illustrated in Figure 1, and was installed for approximately $500,000 AUD, including associated engineering and scientific research costs associated with brine treatment. The pilot was designed to deliver 10 million liters of permeate during the trial. The solar production cost was on the order $50 per cubic meter of permeate production, but production cost would be lower if the plant had been scaled-up and run longer.

The present paper provides an original contribution by providing detailed operational performance of brackish water PV-RO under various amounts of sunshine. The present paper shows how the PV-RO and brine concentration processes are hindered by stormy weather. Rainfall in northern and eastern Australia is correlated with the El Niño Southern Oscillation Index (SOI), being a measure of anomaly in the mean sealevel pressure difference between Tahiti and Darwin [19]. Negative SOI indicates trade wind reversal, pushing moisture away from Australia, to deliver rain onto the west coast of South America. Severe drought in Australia is associated with sustained negative SOI values, and such situations are referred to as "El Niño" in Spanish-speaking South American, because these infrequent commencements of rainfall tend to transpire in December, received in Peru as a Christmas gift. Meanwhile in Australia, sustained depression of the SOI is indicative of weakened wind, increased solar radiation, heat and drought [20].

Under low SOI conditions local governments periodically impose water restrictions in response to drying dams. Restrictions were progressively increased during the Australian drought of the 2000's, with an expectation that all outdoor use of potable supplies would be banned [21]. The present study was commissioned by the Queensland State Government and Brisbane City Council before it became clear that normal rains would return, and so we were allocated resources to experiment with the desalination of brackish bore water for irrigation of the Brisbane Botanic Gardens. With the benefit of hindsight, it appears our project ought to have been funded earlier, as our research infrastructure was only commissioned at the end of 2008 and dismantled at the onset of extreme flooding in 2011. Figure 2 plots the monthly rainfall at the case-study site against as the SOI archives of the Australian Bureau of Meteorology. Figure 3 illustrates monthly litres of water delivered to the Brisbane Botanic Gardens peaked in June and July 2007, averaging over 135,000 litres per day just before SOI moved back to positive values. With respect to various regression curve fits, the R^2 correlation coefficient between SOI and monthly tanker deliveries was greater than 0.2, with variability owing to logistical problems sourcing recycled water and congested traffic in Brisbane. Incidentally the site of the desalination bore has subsequently (2011) been subsumed as headworks of tunnel designed to provide a motorway into the inner city.

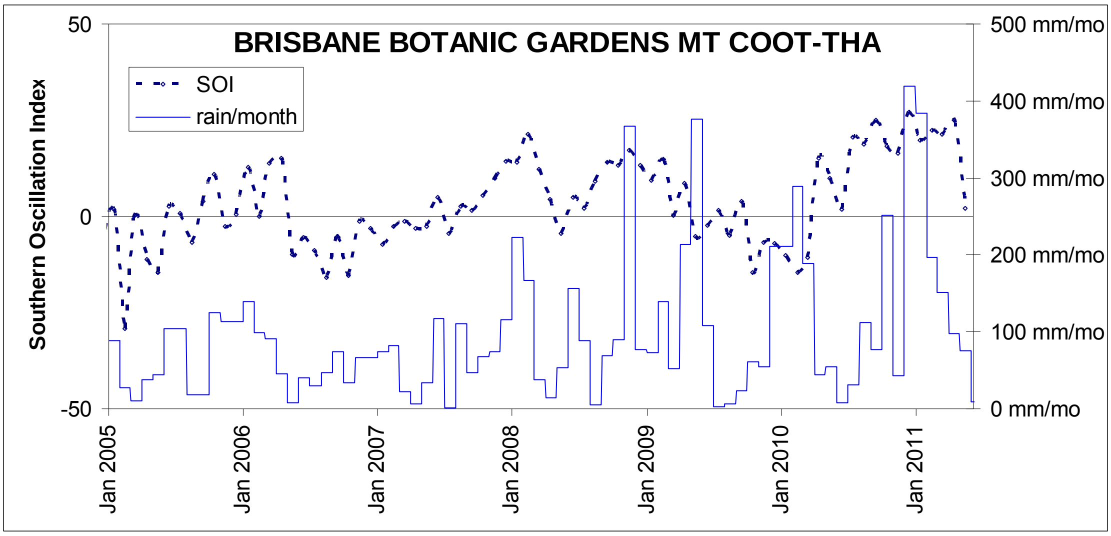

Figure 2: Sustained drought at Brisbane Botanic Gardens is correlated with low ENSO and return of high rainfall correlated with high ENSO.

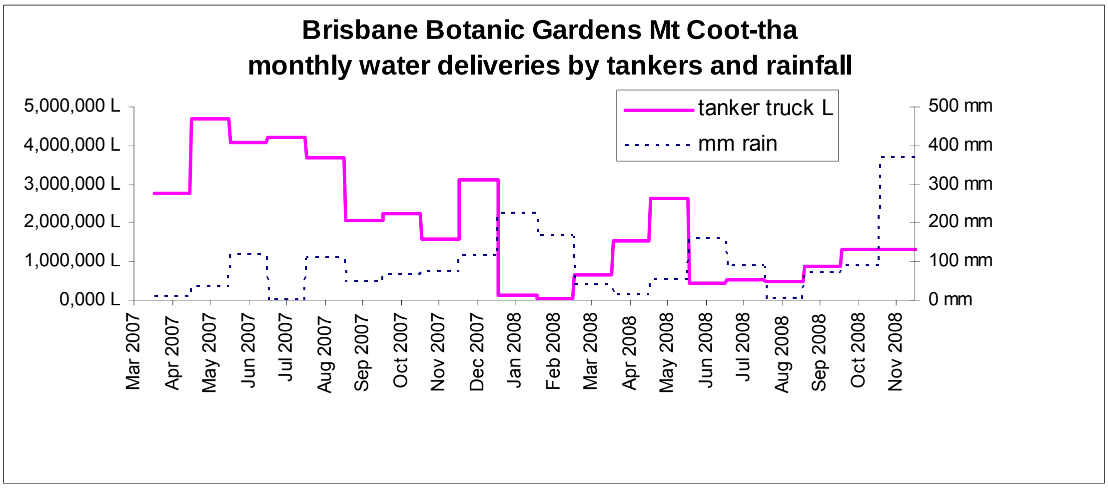

Figure 3: Brisbane Botanic Gardens irrigation water deliveries by tanker truck before commissioning the solar desalination plant was inversely correlated with rainfall and SOI.

Since 1993 brackish water was known to exist in small aquifers under the slopes of Mt Coot-tha, and so a suitable bore was sought in 2006 in preparation for the desalination trial. Geological Survey of Queensland 2002 reports that the substrate is Palaeozoic phyllite, outcropping northwest from Indooroopilly and Toowong. The phyllite is fine grained platy metamorphic rock with very low porosity, weathering to clay at the surface that tends to seal joints and fractures in the matrix. At depth there are occasional small clean fractures, with little water storage capacity, except near gullies where fractures are more likely to occur and there is recharge. The formation is notorious for poor water quality and typically total dissolved solids ranges between 1,000-3,000 mg/L. The borewater is only suitable for very salt tolerant crops and limited stock water use.

The water trucking requirements of Brisbane Botanic Gardens reduced to 13ML through 2008, the year that the desalination pilot plant was designed and installed. The pilot desalination design had been conceived to deliver a nominal 10 ML per annum with the opportunity to install additional capacity if the drought worsened, or if trucking imports became too expensive. The concept design was based on a standard brackish water unit, designed to operate continuously on mains electric power producing 30,000 L per day of permeate and 10,000 L per day of brine concentrate. Since the brackish bore water was slightly artesian with a 1900 mg/L TDS, so the brine reject from the plant would have 7,600 mg/L TDS.

A pair of tracking solar arrays (1.44 kW each) were installed to drive a pair of bore pumps, which feed a bank of reverse osmosis (RO) membranes. One was used to feed the RO bank while the other was held as standby. The standby pump would have been used for a possible future installation of another bank of RO membranes if sufficient brine handling capacity were established. As a botanical novelty, RO brine was directed up the slopes Mt Coot-tha into a series of terrace ponds where marine plants were cultivated to remove salt and concentrate the waste product in a process of evapotranspiration and by means of forward osmosis into the tissue of succulent plants of the genuses *Sacocornia* and *Suaeda*. RO production was constrained by wet season events that would have overflowed the brine treatment system if the desalination process were not occasionally shut down during the trial. Unfortunately we do not have complete records of the incidents when the desalination system was shut down to avoid overloading the brine treatment system [1].

Another research proposition was that the desalination plant could operate part-time powered by tracking solar arrays, and again each night powered by discount off-peak mains power, to deliver 10 ML permeate production in sunny drought conditions, and annual delivery of 20 ML permeate production with a second bank of RO membranes. When mains power was supplied instead of the intermittent supply from the solar array, the installed capacity of the desalination plant proved to be 29.8 L/min with 10.6 L/min brine reject. This proved that an annual delivery of over 15 ML of permeate would be possible with the flick of a switch if non-renewable energy use and brine disposal were not considered to be limiting factors. The desalination plant was designed so that it could also operate on discount-priced off-peak electric power available from the grid. The plant was not operated in this mode as the Garden Manager decided against this [1].

Mains power consumption and all fluid flows were metered to distinguish what permeate production resulted from solar energy, and what production resulted from discounted off-peak mains. For the purposes of the present manuscript it was agreed to only use the mains power for the installation, testing, and maintenance of the desalination pilot plant. Consequently we present operational data for solar desalination, except that controls and backflushing were powered with metered mains electricity. Performance of the brine utility system (marine plant culture) may be discussed in a future publication.

2 Materials and Methods

The green powered desalination trial was conducted at the Botanic Gardens Mt Coot-tha, Brisbane, Australia. Prolonged drought led to severe water restrictions throughout Brisbane years 2005-2008. The Botanic Gardens were disconnected from the water grid as an example to the community, with all water delivered by tanker trucks illustrated in Figure 2 while the desalination system was developed and tested. Some of the water deliveries were recycled fire hydrant test flows, but the most reliable source of tanker water was the almost fresh aquifer (400 mg/L) at Darra.

A brackish bore was established at the Botanic Gardens to a depth of 70m with a pair of Grundfos SQFlex pumps installed 48m below ground in a slotted casing. The pumps were each driven by separate dedicated arrays of 1.44 kW photovoltaic capacity, each. Two parallel sets of electric cable and pump discharge piping were lowered into the bore and laid and backfilled in a 90m long trench to reach a sunny clearing where the solar arrays were installed. The bore was slightly artesian, with 2 meters head above ground. During sunny weather June, July, and August 2008 the pumps proved 45 Litres per minute each (90 L/min together), delivering water 15m elevation uphill to some plant mesocosms that were set up for plant growth trials with the brackish water.
A pulse flow meter and datalogger were installed to measure the brackish bore water that was solar pumped uphill to the marine bed mesocosms before the desalination plant was installed, with a total observation of 519 kL up to that time.

2.1 Analysis of brackish borewater

Before the present research was funded the bore was established and an analysis was provide by Brisbane Water and 20 litres was sealed into a bucket and sent to Victoria University for operation in a benchtop pilot apparatus that continuously desalinated and reblended the permeate and concentrate for many days. This way, the 20 litre sample could endless be recycled to evaluate the possibility of fouling the single 2.5 inch Dow Brackish Water membrane, and to confirm that the simulation program ROSA™ could be used to design a rack for the desalination plant at Mt Coot-tha Botanic gardens.

BCC Scientific Analytical Services preformed a 5th December 2006 grab sample analysis of the raw bore water, reported 21st December 2006 in Table 1 [1]:

Table 1: Analysis of Borewater at Mt Coot-tha Botanic Gardens

Solute	Measured level
Total Alkalinity	460 mg/L as $CaCO_3$
Total Carbon Dioxide	520 mg/L
Free Carbon Dioxide	116 mg/L
Chloride	560 mg/L
Sodium (Soluble)	480 mg/L as Na
Sulphur	150 mg/L as SO_4 (Soluble)
Total Sulphide as S	<0.1 mg/L
Calcium (Soluble)	100 mg/L as Ca
Magnesium (Soluble)	42 mg/L as Mg
Potassium (Soluble)	4 mg/L as K
Soluble Silica	24 mg/L
Iron as Fe	1.7 mg/L
Iron (Soluble)	1.5 mg/L as Fe
Fluoride by ISE	1.1 mg/L
Manganese (Soluble)	0.29 mg/L as Mn
Manganese	0.29 mg/L as Mn
Boron	0.079 mg/L as B
Nitrate N	0.030 mg/L
Nitrite N	0.002 mg/L
Coliforms and E coli	not detected
Heterotrophic Plate Count	7,500 cfu/mL
Field Measurements	
pH	6.9
Conductivity	2,900 µS/cm
Temperature	24.4 °C
Total Dissolved Salt Estimate	1,900 mg/L

Succeeding water quality analysis work was not provided because recovery was run well below where scaling would be expected to occur. Furthermore, there was frequent flushing of the RO membranes whenever power was lost, and so the bore continued to flow regularly. The present paper is focused on operation of the PV-RO process rather than studying any long term changes in the aquifers under Brisbane. Daily logs of bore and permeate conductivity did not show any appreciable change during the course of the trial.

2.2 Reverse Osmosis System

Aqueous Solutions Pty Ltd (ASPL) of Williamstown Victoria was commissioned to inspect the bore late 2007 to provide in-situ SDI tests and to identify if there would be precipitate fouling problems from the borewater being directly pumped from the bore to a reverse osmosis desalination system. The results were satisfactory and so they prepared a brackishwater RO unit without their standard pre-filtration and pressure pumps. Rather they arranged filtration with 10 bar pressure rated cartridge filters arranged 2x2 (two parallel 5 micron units, feeding two parallel 1 micron units). The cartridge filters were required to prevent crude particulates from entering the RO membrane rack. To avoid precipitation, anti-scalant was dosed prior to the cartridge filters. These measures proved to keep the filters and membranes clean after 16 months operation. The RO system comprised 10 units of 4 inch Dow Brackish Water membranes arranged with two trains in parallel, each comprised of two stages (2 × 2), feeding into a combined train of six stages in series (1 × 6). Shutdown was provided by forward-flushing permeate into the feed inlet. Overall system pressure drop was 12 bar, with 2 bar from the bore to the exit of the cartridge filters, and 10 bar from the cartridge filters to the RO permeate.

The desalination plant was installed 28 October 2008 to provide irrigation water, and to benchmark its performance with one of the solar bore pumps driving the process. The effluent brine was treated with a series of hillside terrace ponds that provided a marine plant plant culture that would test the salt removal capacity of harvesting succulent plants for animal foder. So energy was not recovered from the brine stream, rather using the excess pressure to deliver the brine to the hillside marine plant culture. The original flow meter was setup to measure feed into the desalination unit, while additional datalogging meters were installed in the permeate production line, and in a by-pass line that was made available to supply the marine plant culture in case the desalination plant was under service.

The desalination plant was commissioned to utilize off-peak mains electricity from 9 PM 28 October until 6 AM 29 October, producing 16 kL of permeate and 6.8 kL of brine in 9 hours steady operation. After this commissioning, the desalination plant was usually turned off until January when the marine plant culture was prepared to receive the brine stream. The desalination plant was periodically restarted and operated to prime the marine plant culture 27 November to 7 December 2008, but was then turned off until they were prepared. The marine plant culture was prepared 4th January 2009, when the solar desalination plant was again restarted. A member of the botanical gardens staff made log book records of daily observations of flow meters and gauges from 6 January 2009 until 24 February 2010. The solar desalination plant had to be stopped for maintenance of the marine plant culture 27 to 31 January and again 1 to 22 April 2009.

The desalination system controls were programmed to trigger a shut down sequence whenever voltage drop was detected in the circuit driving the bore pumps. Each shut down sequence began by rinsing the RO membranes with permeate for 5 minutes and then resting for at least 20 minutes. Rising solar array voltage was a trigger to restart.

2.3 Tracking solar arrays

Two Grundfos 1.44 kW arrays of 6 x 3 Grundfos GF80 photovoltaic panels, each installed on SunCat™ (Solar Track , Osborne Park, Western Australia) solar trackers. The SunCat™ frames tracked the source of direct normal radiation by a biomimicry system using capillary-tube interconnected counter-weight vessels filled with refrigerant. Both vessels trade roles of evaporation and condensation of the interconnected refrigerant as shade/sun edge creeps over either side. This “propellent” is purportedly not Chlorinated Flouro Carbon. The solar trackers generally kept the solar arrays facing the sun from sunrise to sunset without a motor. The SunCat™ system included automobile shock absorbers that pushed the arrays to face east after sunset. Rain and irrigation-sprinklers cooled off the refrigerant-filled counter weight vessels so that they lost track until the shower stopped. Incident rays of sun are generally held within 23.5º of normal if tracker axis aligned with that of the earth, so arrays receive better than 90% of direct normal solar radiation, plus a view of the diffuse portion of global horizontal radiation as well as some ground reflectance. The tracker axis must be set to geographic latitude.

The GF80 solar panels were designed to be wired eight-in-series to produce 266 volt nominal direct current into the Grundfos SQFlex pumps. GF 80 solar modules were multicrystalline silicon in series with bypass diodes, laminated between ethylene vinyl acetate and 3 mm high transmissivity, low-iron tempered glass. Peak power output of GF80 solar panels was rated at 80 Watts with 33.3 voltage and 2.4 amperage at 1000 W/m² insolation.

2.4 Pumps

Two identical pumps were provided in the borehole with two independent solar arrays. Each was a Grundfos SQF 2.5-2 Helical rotor pump (3"), with stainless steel casing, carbon/ceramic bearing, with power transmission via micro frequency converter driving 50 Hz permanent magnet rotor with segmented stator. The SQF pump motor operates at any voltage between 30V and 300V DC or 90 to 240V AC, and the performance curve is shown in Figure 4. The system curve of the bore-feed desalination system is overplotted, assuming a pressure requirement of $\Delta p = f \times \text{feed} + 77.4$ kPa where the constant f = 24.37 kPa.minute.litre^{-1} and feed has units of litre.minute^{-1}. Consequently 1.44 kW maximum power supplied to one pump by the corresponding solar array resulted in 120 meters head (12 bar) with 44 L/m flow (2.6 m³/hr). A number of relationships were tested using Microsoft Excel, and there was little or no improvement no matter how much higher the order of the polynomial of fitting with respect to pumping kW power.

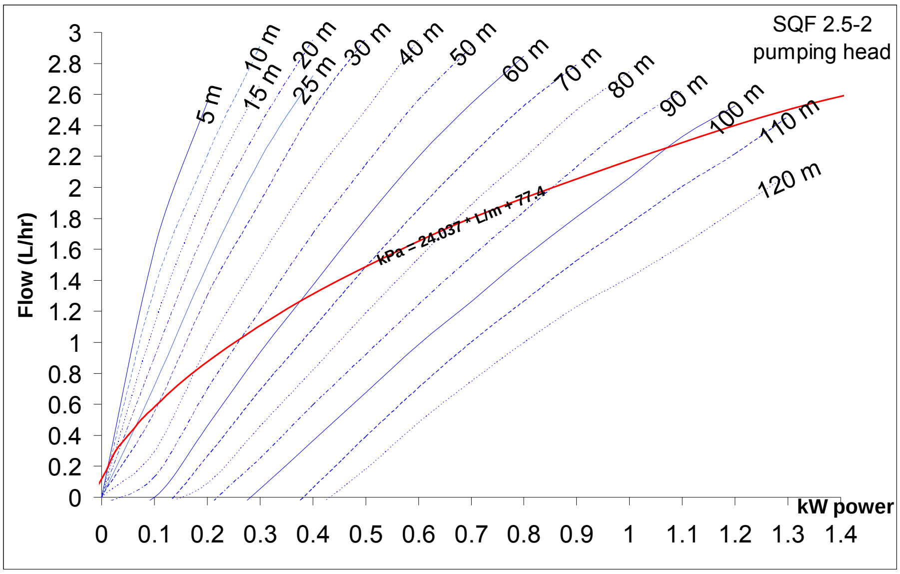

Figure 4 Grundfos SQF 2.5-2 Helical rotor pump performance at 3000 rpm with bore-desalination system curve overplotted. System curve also fits (R^2 = 0.993) flow (L/s) = $-4.7371\text{kW}^6 + 23.262\text{kW}^5 - 43.95\text{kW}^4 + 40.513\text{kW}^3 - 19.64\text{kW}^2 + 6.6239\text{kW} + 0.1$ L/s.

Grundfos CU SQFlex controller was required for each pump, and displays status, but unfortunately without datalogging capability. Manufacturer allowed for up to 200 m wiring between bore pump and controller, which in our situation was integrated with the desalination control system.

Data that Grundfos downloaded from the pump motors on Monday 8th March 2010 at the conclusion of the trial showed Pump #1 provided the desalination service for 16 months trial, running 3326 hours. While Pump #2 ran 311 hours, providing bypass feed to the marine plant culture before and during the desalination trial.

2.5 Daily Solar radiation data

Preliminary daily sunshine hour estimates were posted at the Australian Bureau of Meteorology (BoM) website, but only archived for one year. The authors are not aware of the exact BoM method for estimating sunshine hours, and the BoM only provides such data for a limited number of locations with manual hourly observations. The nearest location to the case study site was the Brisbane International Airport, 10 km from Mt Coot-tha Botanic Gardens. The BoM website also provides an integrated daily global horizontal (DGHI) radiation time-series at all rain-gauges and weather station stations (thousands of locations in all), spanning the continent, including the Mt Coot-tha Botanic Gardens. These DGHI timeseries were based on hourly satellite observations, adjusted by the nearest ground based observations.

2.6 Hourly Solar radiation data

The hourly solar radiation data was derived from satellite imagery processed by BoM from the Geostationary Meteorological Satellite and MTSAT series operated by Japan Meteorological Agency. The BoM uses hourly images to estimate hourly instantaneous solar global horizontal irradiance (GHI) at ground level, based on a two-band physical model [22]. Each GHI value is converted to a direct normal irradiance (DNI) value by applying an algorithm which depends on the GHI values and solar geometry and the diffuse fraction estimated by applying a modified form of the Ridley model [23]. The diffuse fraction (ratio of diffuse irradiance to GHI) is modeled from instantaneous clearness index (ratio of GHI to extraterrestrial irradiance), daily mean clearness index, solar elevation, apparent solar time, and a measure of temporal variability instead of the "persistence" parameter adopted by Ridley et al. Model coefficients were fitted to observations of GHI and DNI from BoM's surface radiation network, which were 1-minute observations taken at 1-hour intervals to simulate the satellite sampling. DNI accuracy was estimated by comparison with 1-minute averaged DNI measurements from BoM surface-based instruments. The mean bias difference (average of the satellite - surface difference) was typically around +30 W/m². This is +5% of the mean irradiance of around 540 W/m². The root mean square difference, calculated on a similar basis, was around 150 W/m², which was 30% of the mean irradiance. The source of uncertainties associated with calculation of DNI includes uncertainties in:

- anisotropy of cloud-top reflectance;
- water vapour in the atmosphere;
- satellite calibration; and
- the GHI-to-DNI conversion model.

BoM metadata notes that a particular DNI value may not be representative of a 1-hour period, due to variations in the solar zenith angle during the hour, and most significantly because of variations in atmospheric conditions such as cloudiness. The authors did not transform GHI to DNI but rather obtained these separate datasets from the Australian Bureau of Meteorology to estimate isolation on the tracking PV array.

3 Results

The results of the solar desalination trial are plotted in two time-series, each eight months (242 days) long, in Figure 5 (November – June) and Figure 6 (July - February). The datasets join where the Australian fiscal year breaks, ten days after the winter solstice. Trials are subtotaled at 30 June to account for the productivity during the southern hemisphere summer having greater solar energy and monsoonal rain.

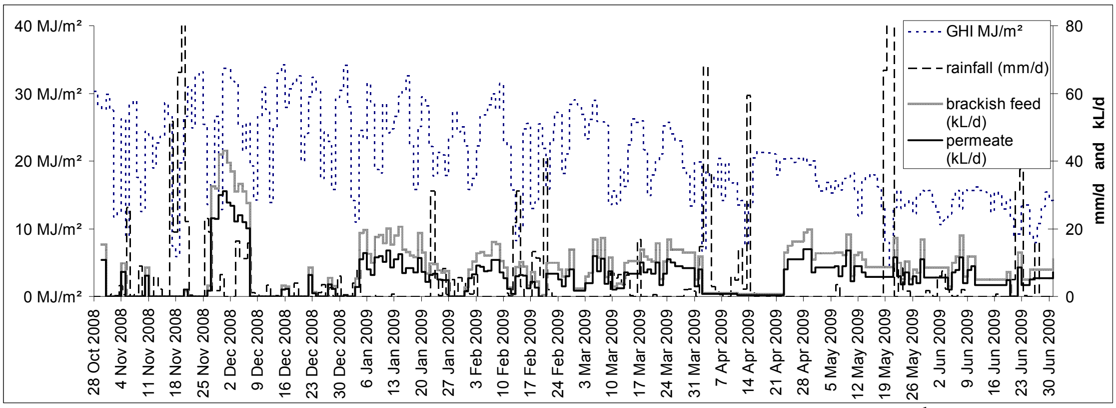

Figure 5: Desalination operation in the first fiscal year, concluding 30th June 2009

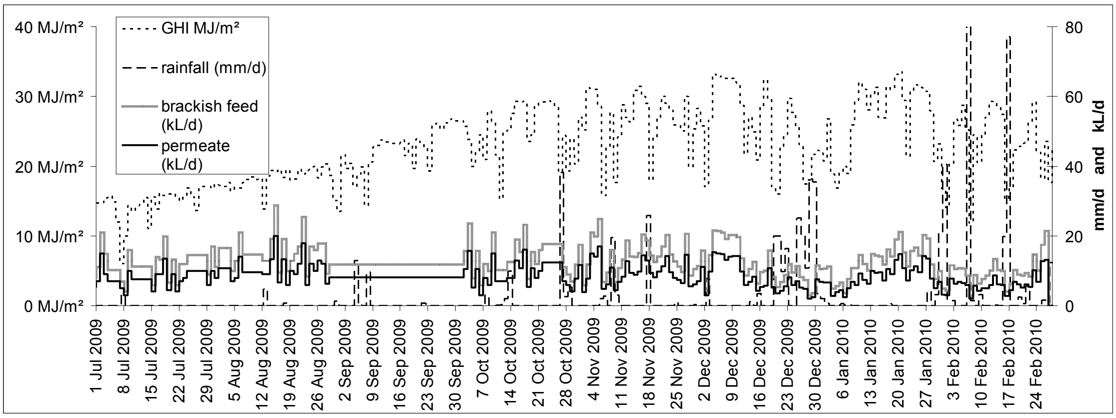

Figure 6: Desalination operation in second fiscal year, commencing 1st July 2009

As a comparison, 1.316 ML of permeate was produced in the period ending 30 June 2009, whereas 2.050 ML was produced in following 242 day period. It should be noted that zero daily permeate production was a consequence of the system being shut down during development and maintenance of the marine plant culture during the first period. Also note the non-zero horizontal segments of permeate productivity are an artifact of infrequent manual meter reading at times that automatic data-loggers were not operating.

Total period of reverse osmosis permeate production is plotted by month in Figure 7. Notice permeate production rate was hindered with positive values of SOI. Month-long average of daily production (L/d) = $-0.0046 \times (SOI)^2 - 0.11 \times SOI + 7.4$ fitted with $R^2 =$ 44%. Note that demand for flushing was metered in the last month of the trial, in February 2010. While the recovery rate appeared to be 65%, the amount consumed in flushing could be argued to have reduced the overall recovery rate to 49%. On the other hand, the flushing water need not be considered a brackish product and was usefully applied in irrigation of the gardens, or restored to the permeate storage tank.

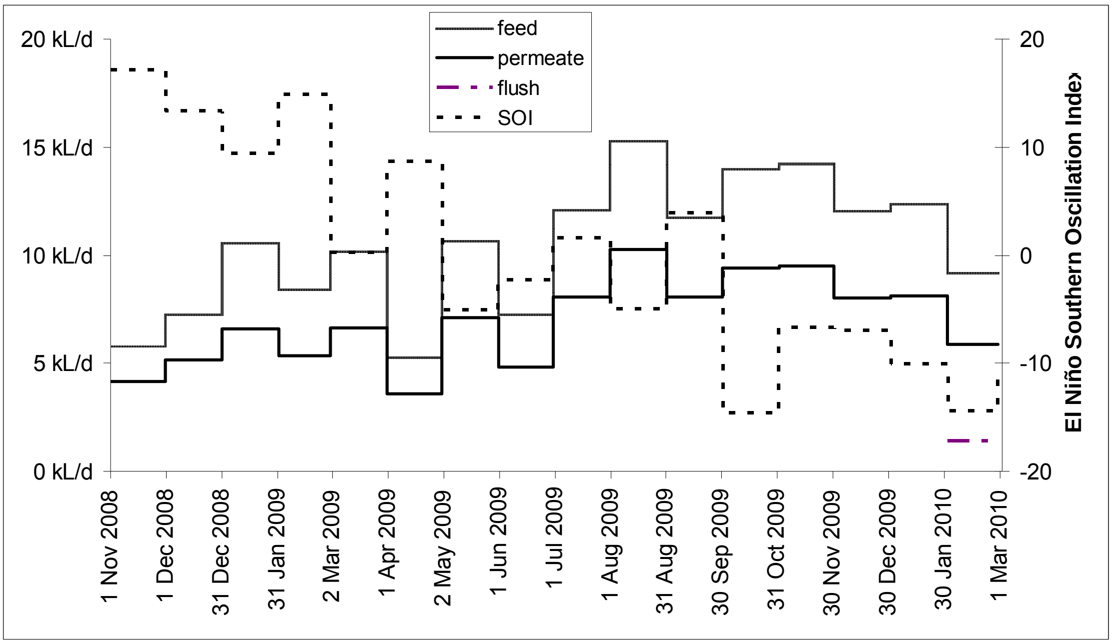

Figure 7: Whole 16 month period from November 2008 through February 2010.

Further examination of higher resolution data was possible in the period November 2009 to February 2010, as illustrated in Figure 8. This shows that 57% of the variability in production performance is predicted with daily GHI, and demonstrates that daily GHI is a dominant parameter for predicting the production from solar driven RO plant with a tracking array. Detailed modeling of hourly insulation on the tracking array failed to prove a better correlation with permeate production. The daily accumulated GHI is likely to smooth over instantaneous misalignments of the tracking array, and overcome the patchiness of individual clouds cruising over the landscape. The alternative modeled array insolation from hourly values of GHI as well as DNI required precision management of a terabyte-scale hard drive of ASCII raster files supplied by the BoM. The alternative model is beyond the scope of the present paper, but it should be noted that it proved to be a copious task that ultimately did not yield a better predictor of performance.

Even higher resolution understanding of system performance is provided in Figures 9 and 10 (15 and 23 February 2010), plotting hourly DNI and GHI as well as feed rate into the reverse osmosis rack and permeate production rate.

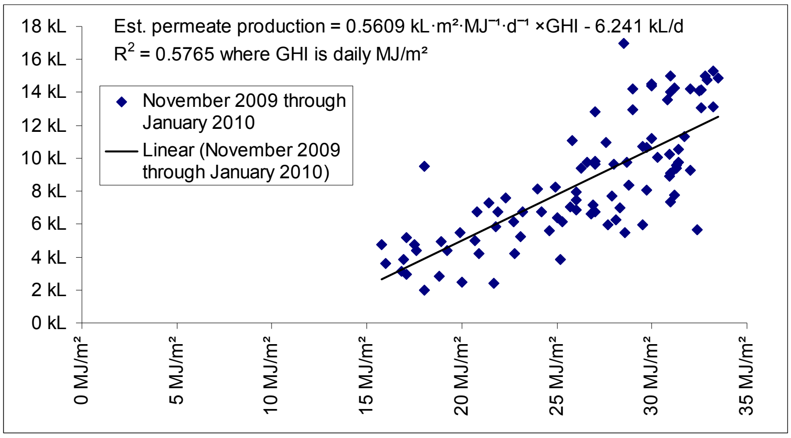

Figure 8 Daily permeate production November 2009 through February 2010 as a function of daily global horizontal insolation (GHI).

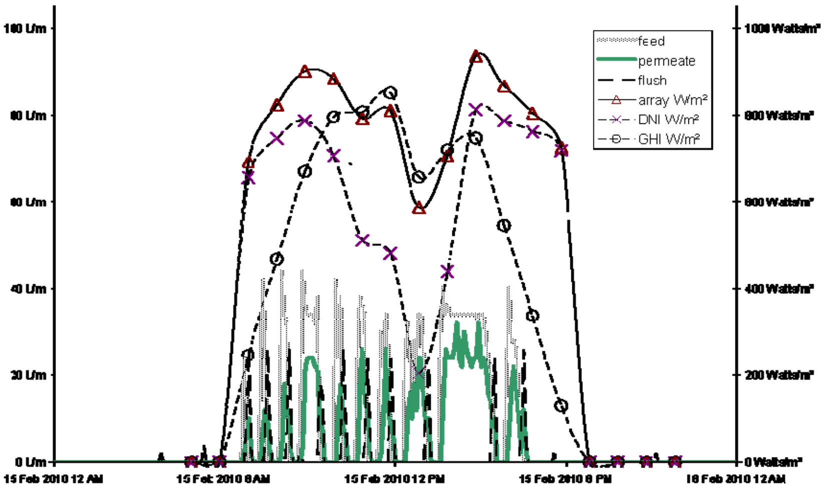

Figure 9: 16th February 2010. Raw recovery 59% and flushing 31%, delivering 41% overall.

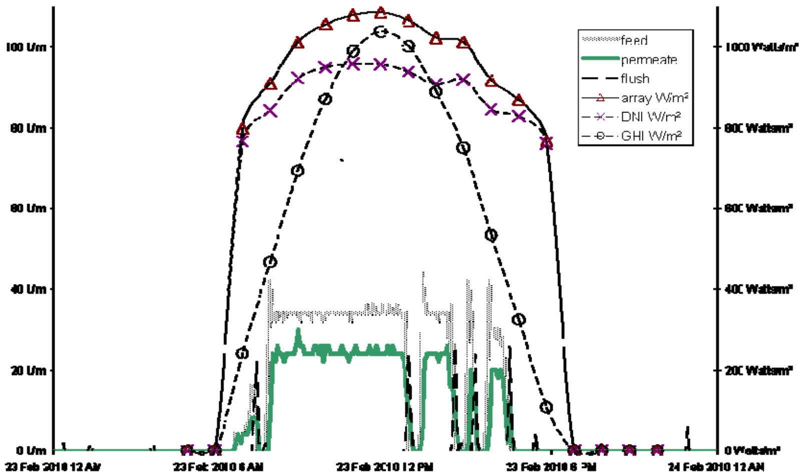

Figure 10: 23rd February 2010. Raw recovery 68% and flushing 10%, delivering 61% overall.

The irradiation on the photovoltaic array was modeled assuming isotropic diffuse radiation and ground reflectance, but the correlation with feed and permeate production was no better than using GHI or DNI as the independent variable. The spatial and temporal resolution of the hourly satellite estimates of GHI and DNI were not sufficient to capture the fluctuations in desalination performance as individual clouds intermittently shaded the photovoltaic array. For example, the bursts in flushing rate illustrated on 15 February 2010 as a consequence of partly cloudy weather that caused the desalination system to shutdown and go into hibernation mode 10 times before the end of the day, while periods of clear sun on 23rd February 2010 were interrupted only 4 times before the end of day shut down. On inspection of high resolution time series of water flow rates it is surmised that short periods of sunshine resulted in low production – determination of the exact correlation would require ground-based sunshine data logging. Failing this it appears that GHI is the most readily available performance predictor for solar photovoltaic performance. Other countries between Australia and Japan could make use of this dataset. Daily timeseries of GHI coincident with rainfall are now freely available from the BoM Website www.bom.gov.au/climate for thousands of Australian locations so that rainwater harvesting and solar borewater desalination can be locally assessed. The same sort of dataset could be developed at virtually any rainguage location north of Australia that is in the view-field of the geosynchronous provided by the Japan Meteorological Agency. World-wide estimates of GHI can be obtained from NASA's surface meteorology and solar energy (SSE) dataset (http://eosweb.larc.nasa.gov/sse/). As such, GHI data might be useful for estimating the design capacity of solar PV-RO systems, and provide greater confidence to designers of such systems.

Another possible predictor of system performance is the daily "sunshine hours". Comparison between sunshine hours and brine reject rate is shown in Figure 11.

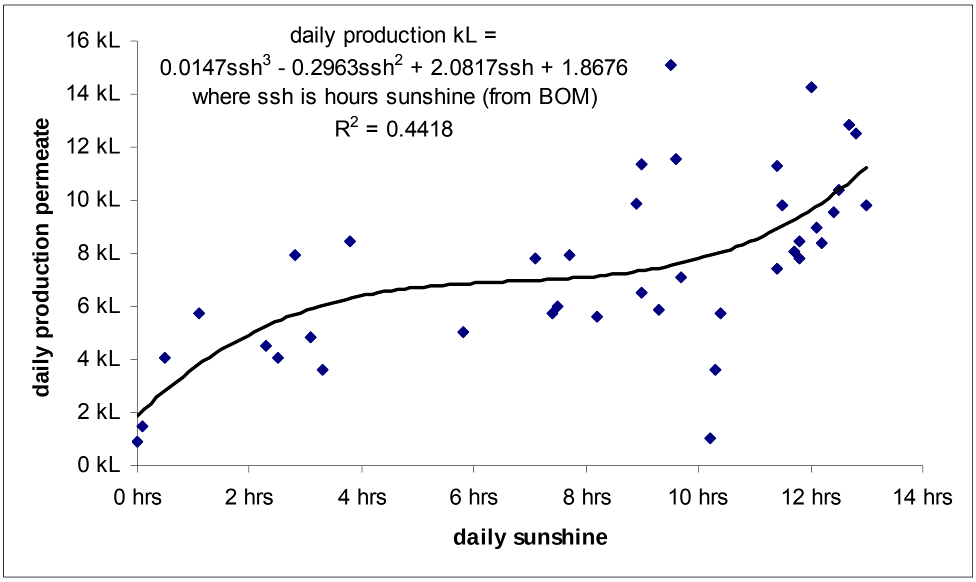

Figure 11 Solar Pumping of brine to marine plant culture as function of sunshine hours January - February 2009. Permeate production sorted by sunshine hours.

Preliminary observations by meteorologists based at Brisbane Airport YBBN, Daily "sunshine hours" reported as the total hours of direct sunshine observed on one day. This metric provides no information about the pattern of cloud. We found sunshine hourse to be predictor of 44% of the variability of brine delivery to the marine plant culture during the early stages of the project January – February 2009. The performance of solar pumping into marine plant culture at Mt Coot-tha Botanic Gardens was compared to sunshine hours observed at the opposite side of the City of Brisbane, at the seaside international airport. The airport sunshine hours estimated by the Australian BoM are posted on their website for one year, and then discarded. Daily GHI is now freely available from the BOM website for virtually any locality in Australia with a rain guage, and so the authors recommend other that users use that metric to assess solar desalination potential and concurrently assess rainwater harvesting opportunities. Countries north of Australia could make arrangements with the Japan Meteorological Agency to provide coverage in the view of the same geostationary satellite.

It can be surmised that an instantaneous burst of sunshine correlates with desalination system production by understanding the relationship between pumping pressure and the performance of the reverse osmosis system. To this end, the log-book records of pressure gauges and flow meters recorded by a member of the botanic gardens staff at approximately 10 AM on hundreds of occasions were plotted as shown in Figure 12. Based on instantaneous readings, system pressure predicts about 94% of the variability in feed, brine rejects, as well as production of permeate.

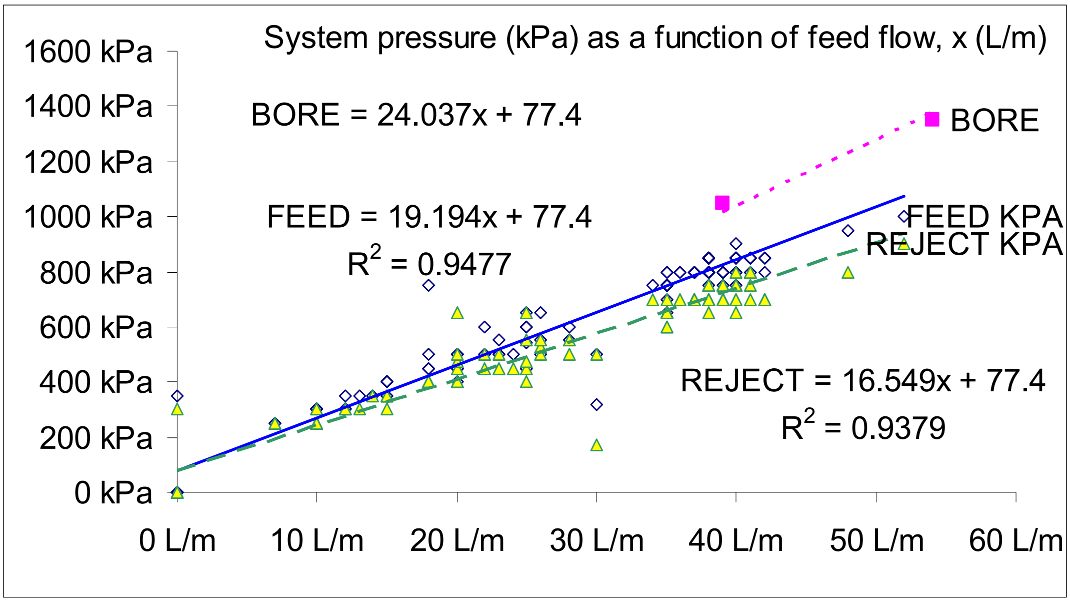

Figure 12 Analysis of pumped performance. Based on daily logbook observations Jan 2009 through February 2010. The intercept of curves is 77.4 kPa artesian pressure.

The trial of the photovoltaic pumped reverse osmosis desalination system did not know a-priori what would be the power requirement of controls and backflush systems associated with the commercial desalination system that was employed. So an alternative source of electric power was provided to keep these systems energized, as well as to provide lights and power points in the building that housed the desalination system, and also to supply power to a pump that transferred the permeate production to the Australian Rainforest Catchment of the Mt Coot-tha Botanic Gardens. A three phase power meter was measured these loads. The total electric energy required to drive the lights and desalination system controls and backflush pump "desal" was only 1.1 kW-hours per day, with a maximum instantaneous demand of 1 kW.

Comparisons with another PV-RO trial without batteries and inverter [24] in Mesquite, Nevada, bore water had a salinity of 3,500 mg/L total dissolved solids. During their 3 month field test, energy use per volume of water produced was 1.38 kilowatt-hours per cubic meter. They encountered problems with scaling with the intermittent behavior of solar power, and did not benefit from the generous flushing of our prototype.

Ghermandi and Messalem [25] reported that a couple of other tracking systems perform better than fixed tilt arrays, but in the mentioned case studies productivity was substantially smaller scale than our work. Our overall ranking would be near the top three if Ghermandi and Messalem had compared our specific energy in Figure 13. Equation 1 suggests a relationship between energy input and TDS as follows.

$$\text{Specific energy consumption, SEC} = \text{coefficient} \times \text{TDS} + \text{overheads} \qquad \text{(eq 1)}$$

The coefficient includes practical RO systems pressure drops, and also factors the osmotic pressure associated with the units of TDS/SEC, while the overheads represent operational effects such as flushing cycles. Performance below the linear regression curve is relatively "good" and can be explained by lower parametric values of the coefficient and/or lower overheads.

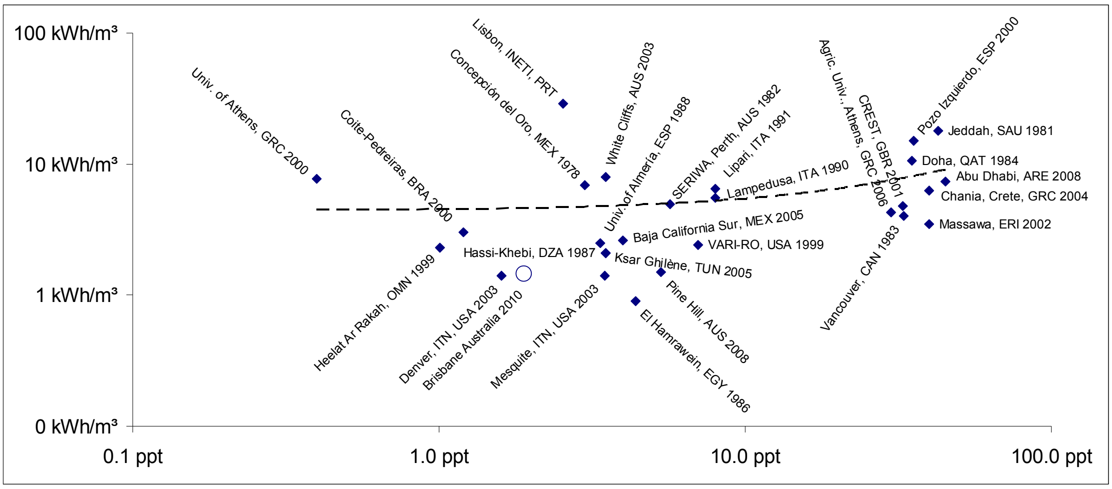

Figure 13: Specific energy consumption of the present findings (open circle) compared to other PV-RO systems reviewed by Ghermandi and Messalem [25] (solid diamonds). Note the broken line is linear regression fit, establishing that specific energy consumption tends to increase with total dissolved solids, plotting TDS ppt (g/L) in the horizontal axis.

Factors that contributed to the present finding of low specific energy consumption included: the 1900 mg/L TDS having a low osmotic pressure, the tracking solar arrays maintaining full power on sunny days, avoidance of batteries, and our utilization of bore pump pressure to drive permeate and rejects to their destinations. Our system shared an avoidance of batteries with another low specific energy exemplars of brackish borewater desalination [24], as water storage is more efficient and economical than energy storage [25]. Our plant ran for a substantially longer trial period without fouling of membranes, where as the exemplar [24] trial lasted only 3 months. This may be attributed to Aqueous Solutions set up permeate flushing of membranes repeatedly during the day whenever pump pressure was lost, with the result of our loosing energy efficiency in favor of reliability. On the other hand we provided the tracking solar array that the other exemplar [24] suggested in their conclusions but did not manage to implement.

We also arranged our system to direct bore water into the RO membranes without pretreatment, to avoid precipitation of minerals before we were prepared to feed the TDS load through the membranes. In our system, precipitates occurred after discharge into brine treatment ponds where acidity was buffered and dissolved oxygen entered the stream.

4 Conclusions

A "Green Powered Desalination" plant ran for a 16-month period from November 2008 through February 2010, producing 3.36 million litres of permeate in 484 days of variable sunshine. Further production was constrained by wet season events that would have overflowed the brine treatment system if the desalination process were not occasionally shut down during the trial. The maximum sustained production rate averaged 10,270 litres per day of permeate production over the month of August 2009, a sunny winter dry-season exemplar, with a negative Southern Oscillation Index, SOI = -5. Production tended to decrease with positive SOI (wet months).

Whatever the energy driving flow through membranes, pressure is strongly correlated with reverse osmosis desalination performance. Daily logbook observations indicate 94% of the variability in permeate production was determined by sustained driving pressure. But overall daily desalination recovery rates proved to suffer with intermittent pumping, as there were flushing overheads associated with each hibernation cycle. This was necessary to avoid scaling of the membranes at times when pumping failed due to clouds.

The best available operational correlation of PV-RO production was with the daily global horizontal irradiation (GHI), with 57% of variability predicted by this parameter. It was found that on the order of 30 MJ/ m^2 per day of GHI was sufficient for our equipment to operate at its rated capacity.

Circa 30 MJ/m^2 GHI per day → high PV-RO production

A readily available predictor of the need for irrigation requirement in eastern Australia are low values of the El Niño Southern Oscillation Index (SOI), and now we suggest that negative SOI values also indicate that solar desalination of brackish borewater may be able to meet irrigation requirements in an Australian east coast setting.

Positive SOI ≈ Rainy weather → low irrigation requirement
Negative SOI ≈ Sunny weather → high desalination production

In years with above average rainfall, stormwater harvesting may be appropriate. It is suggested that location-specific timeseries of rain and GHI should be developed in other situations where SOI is not consider a useful metric of wet weather.

The focus of future work should be on the tools for estimating production from course solar data. Extra refinements would need to include data from small time intervals but this is unlikely to be available. It could be possible to improve performance of RO plants by optimizing the permeate flushing arrangements, but in this work that water was not wasted but used for irrigation.

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